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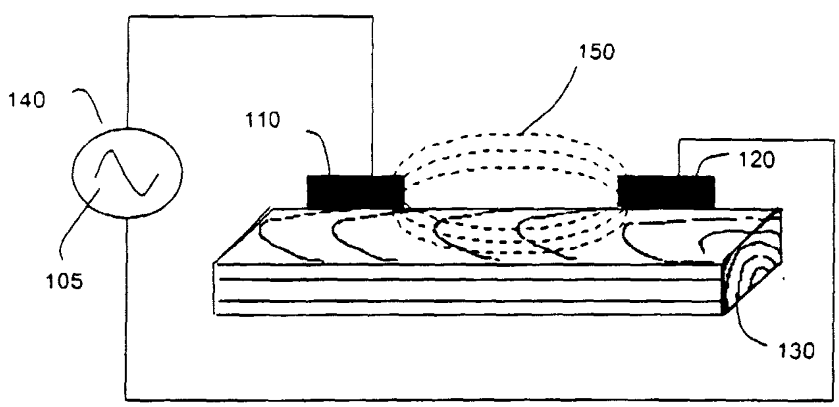
(54) Title: MOISTURE AND DENSITY DETECTOR (MDD)




(57) Abstract: A Moisture and Density Detector (MDD) that provides a method and apparatus to determine the moisture content and/or density of any dielectric material for various purposes. This device is very useful in detecting the moisture content (MC) of wood and wood-based materials, such as that of lumber in a dry kiln prior to, during and/or following drying. The MDD passes a radio frequency signal between opposed or adjacent capacitance electrodes and measures the signal strength and phase shift of the signal. The addition of phase shift and multiple frequencies improves the accuracy of the results.

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## TITLE OF THE INVENTION

## MOISTURE AND DENSITY DETECTOR (MDD)

## FEDERALLY SPONSORED DEVELOPMENT

This invention was made with U.S. Government support under grant number 00-34158-9035 awarded by the Department of Agriculture. The U.S. Government may have certain rights in this invention.

## BACKGROUND OF THE INVENTION

### Field of the Invention

The present invention, the Moisture and Density Detector (MDD), relates to an apparatus and method for detecting the moisture content (MC) and/or density of dielectric materials.

### Related Art

*Moisture Estimation Using Radio Frequency Signals*

Several devices have been developed to measure moisture in materials. These devices are based primarily on resistance and capacitance principles. Resistance is the opposition of a body or substance to a current passing through it. Capacitance is the property of a circuit element that permits it to store charge. For resistance devices, a direct current (DC) radio frequency signal is passed through a dielectric material (a material that does not conduct electricity) and the signal strength is measured as a function of the resistance of the material. This resistance measurement is then converted to a moisture content (MC) value using correction factors for temperature

and species. Capacitance devices measure capacitance value or "power-loss" and estimate MC based on known correlation.

U.S. Patent 4,259,633 to *Rosenau* describes a resistance MC estimation technique. The technique applied by *Rosenau* and others is limited in that it requires that metal pins be inserted into the wood sample being tested. In addition, the electrolytic polarization effects when using DC voltage can result in measurement error. Inserted-pin resistance devices are considered to provide inaccurate estimates when the wood MC is above the fiber saturation point of 24 to 30 percent.

U.S. Patent 3,600,676 to *Lugwig et al.* teaches the capacitance technique whereby an alternating current (AC) radio frequency capacitance device was developed using adjacent electrodes and resonance to determine the MC of bulk materials (i.e., coal, chips, etc.). This device applies a range of frequencies to the dielectric material adjacent to the electrodes. The frequency with maximum signal strength is termed the resonant frequency and is a direct function of the MC of the dielectric material. The *Lugwig et al.* device determines the resonant frequency at which signal strength (amplitude) reaches a maximum. Applicant's invention also applies a range of frequencies to the dielectric material and measures the signal strength of each in terms of amplitude. However, Applicant's invention does not determine the resonant frequency but rather relates the measured amplitude of each frequency to predetermined values to determine the MC of the dielectric material. In addition, in contrast to Applicant's invention, the *Lugwig et al.* device does not use phase shift as additional information to estimate MC or density.

U.S. Patent 4,616,425 to *Burns* describes an opposed electrode device based on resistance or capacitance controlled oscillator circuits. Whether based on resistance or capacitance, this device requires conversion to a frequency-dependent

DC voltage. Signal strength of the DC voltage is related to predetermined voltage values for the dielectric material to allow MC estimation. Direct contact with the dielectric material is required. In contrast to *Burns*, Applicant's invention does not employ conversion from AC signal to DC signal. In addition, direct physical contact with the wood surface is possible, but not necessary. Furthermore, *Burns* does not use measurement of phase shift to improve the MC estimate. The *Burns* device also has no capability to estimate dielectric material density.

U.S. Patent 3,430,357 to *Perry* discloses an opposed electrode device that measures capacitive impedance and associated MC in a stack of lumber in a dry kiln. The resistance between a capacitance probe inserted several courses of lumber above a ground electrode gives a measure of stack MC in the lumber between the electrodes. This method requires direct contact between the capacitance probe and the lumber. With the *Perry* device, an AC signal is converted to a DC signal prior to measurement of the signal strength as voltage. *Perry* differs from Applicant's invention in that Applicant directly measures the strength of the AC signal. *Perry* also does not employ a phase shift measurement to improve the MC estimate. In addition, the *Perry* device has no capability to estimate dielectric material density.

U.S. Patent 4,580,233 to *Parker et al.* teaches an adjacent electrode AC moisture sensing device with two alternating frequencies that measures the imbalance in a capacitance bridge to estimate the MC of dielectric materials. Circuitry and methodology is incorporated to correct for potential wood temperature differences. As with the *Lugwig et al.*, *Burns*, and *Perry* disclosures, the AC signal is converted to a DC signal prior to measurement of voltage to determine signal strength. This

differs from Applicant's invention, which directly measures the strength of the AC signal. In addition, *Parker et al.* does not employ phase shift either to improve the MC estimate or to allow for estimation of dielectric material density.

U.S. Patent 5,402,076 to *Havener et al.* recites a portable device, similar to *Perry*'s device, that measures MC in a stack of lumber but with the AC radio frequency signal transmitted between adjacent electrodes. As with *Perry*, Applicant's invention differs because Applicant measures the phase shift and has the capability to estimate wood density.

U.S. Patent 5,486,815 to *Wagner* discloses an in-line AC moisture meter employing opposed capacitance electrodes to sense MC in lumber moving between the electrodes. A single 4 MHz frequency is transmitted between electrodes and the received signal strength is measured to provide an estimate of the wood MC. The 4 MHz signal is applied to two pairs of electrodes with a 20-volt peak-to-peak amplitude signal applied to one pair and a 4.5 volt peak-to-peak amplitude signed to the other. The 4.5 volt signal is applied 180° out-of-phase with the higher 20-volt signal. *Wagner* teaches that analysis of the out-of-phase signal responses reduces the effects on the signal of electrical loading of the material. *Wagner* differs from Applicant's invention because *Wagner* does not improve the estimate of MC by adding phase shift information and *Wagner* has no described capability to estimate the dielectric material density. This device is also limited to detection of MC below 24 percent.

The teachings described above have employed measures of signal strength of both resistance and capacitance electrodes to estimate dielectric material MC. Both AC and DC devices have been developed. However, none of the described devices are reportedly accurate in measuring MC above the fiber saturation point of approximately 24 to 30 percent MC. In addition, none have employed measurement

of signal phase shift to improve their estimate of MC. Furthermore, none report the capability of estimating the density of the dielectric material by combined analysis of amplitude and phase shift of a radio frequency signal.

U.S. Patent 5,086,279 to *Wochnowski* discloses a means for estimating MC in a stream of materials by both reflecting and passing electrical energy through the stream in the form of infrared, microwave, or energy generated by a high-frequency oscillator circuit. For each of the electrical energy types, the energy is both reflected from and transmitted through the material stream. The transmitted energy from the high-frequency oscillator may be inferred to be in the same radio frequency range as Applicant's invention, although *Wochnowski* did not define the spectrum.

The *Wochnowski* MC estimate of the stream of materials depends on measures of signal strength and phase shift with each obtained by two methods. The two methods are to obtain a reflected signal detected by a sensor on the same side of the stream of materials and also a through signal such as is obtained by an opposed or adjacent electrode configuration. Therefore, the MC estimate provided by *Wochnowski* depends partially on the correction for the mass of the stream of materials by analysis of the "damping of oscillations" of electromagnetic waves through a first signal and a second (reflected) signal. Likewise, additional information for the MC analysis is obtained from the phase shift of both a through and reflected signal.

Applicant's invention differs from *Wochnowski* in that it requires no information on reflected energy but depends solely on its estimate of MC and density based on passage of the signal between the electrodes. In addition, Applicant compares phase shift and signal strength changes, caused by interaction of the radio frequency signal with the dielectric material, to predetermined values to provide the estimation of MC and density. *Wochnowski* describes no method for comparing

predetermined values to correlate measured phase shift and signal strength decrease to expected values for the dielectric material at given MC's and densities. Applicant also provides an estimate of dielectric material density that the *Wochnowski* device does not provide.

In a 1993 writing, *Torgovnikov* discloses dielectric constants, measures of signal strength, and loss tangent values for radio frequencies from 20 to 1000 Hz. G. Torgovnikov, DIELECTRIC PROPERTIES OF WOOD AND WOOD-BASED MATERIALS 174-181 (1993). (The terms loss tangent and phase shift are both referenced herein. While these terms differ in their meaning, they are mutually direct functions with one easily derived from the other. For this reason, devices designed to provide information for one also indirectly provide the other value. In that sense these terms will be used interchangeably.) For all frequencies tested, *Torgovnikov* shows via plotted regressions that the rate of increase in the dielectric constant is higher for MC below the fiber saturation point. The plotted slopes of the regression lines also appear to have significant slope above the fiber saturation point. These plotted regression lines, however, represent the mean dielectric response for a range of wood specific gravity values.

*Torgovnikov* also teaches that the dielectric response is strongly influenced by the wood specific gravity. Therefore, dielectric constant information alone will not allow an accurate estimation of wood MC because of the confounding influence of wood density. With current methods this confounding influence can only be eliminated if a single wood density is scanned or if the density of specimens is known.

*Torgovnikov* does not provides a method to improve MC estimate by including phase shift or loss tangent as a predictive variable.

*Moisture Estimation Using Microwaves*

Attempts have been made to measure the MC of materials using microwave energy. U.S. Patents 4,727,311 and 5,767,685 to *Walker* teach ways to measure the MC of materials such as sand and coal. In these cases, two microwave frequencies are passed through a material in order to determine MC. The difference between the two signals assists in determining MC.

U.S. Patent 4,674,325 to *Kiyobe et al.* calculates MC by passing material between non-contacting microwave horns. The basis weight is detected with an ionizing chamber.

U.S. Patent 5,315,258 to *Jakkula et al.* discloses a radar system developed for measuring the MC of materials. There, the change in velocity of the microwaves within the material is correlated to differences in MC.

The *Walker*, *Kiyobe et al.*, and *Jakkula et al.* teachings differ from Applicant's invention in that a microwave signal rather than signals in the radio frequency spectrum are utilized. Microwave devices require wave guides to transmit and receive the signals while radio frequency devices such as the Applicant's require only electrodes. These microwave devices described also do not have the capability to estimate dielectric material density.

The following disclosures describe microwave devices based on the attenuation of the microwave signal to estimate moisture content combined with information on phase shift of the microwave signal to provide wood density information:

1. R. King et al., *Microwave Measurement of the Complex Dielectric Tensor of Anisotropic Slab Materials*, *in* PROCEEDINGS OF A TECHNOLOGY AWARENESS SEMINAR (Nov. 15-16, 1987).
2. R. King et al., *Measurement of Basis Weight and Moisture Content of Composite Boards Using Microwaves*, *in* PROCEEDINGS OF THE 8TH SYMPOSIUM ON THE NONDESTRUCTIVE TESTING OF WOOD (Sept. 23-25, 1991).
3. P. Martin et al., *Evaluation of Wood Characteristics: Internal Scanning of the Material by Microwaves*, *in* 21 WOOD SCIENCE TECH. 367-371 (1987).
4. P. Martin et al., *Industrial Microwave Sensors for Evaluation of Wood Quality*, *in* FOURTH INT'L CONFERENCE ON SCANNING TECHNOLOGY IN THE WOOD INDUSTRY (1991).
5. J. Portala & J. Ciccotelli, *Nondestructive Testing Techniques Applied to Wood Scanning*, *in* 2 INDUSTRIAL METROLOGY 299-307 (1992).

*King et al. (1987), King et al. (1983), Martin et al. (1987), Martin et al. (1991),* and *Portala et al. (1992)* depend for their estimates of MC and density on the analysis of both attenuation and phase shift. Microwave devices differ from Applicant's device in that microwave frequencies are in the range above 1000 MHz. For frequencies in this range waveguides that are much more costly than the electrodes of Applicant's device are required. No radio frequency device has been disclosed that combines analysis of changes in signal amplitude and phase shift to estimate wood MC and density, with the exception of *Wochnowski*. As discussed, this device requires information on both reflected and through-material amplitude and phase shift signals to obtain estimated material MC and density.

<u>Radio Frequency Moisture Gradient Estimation</u>

An impedance detector disclosed by *Tiitta et al.* measures the moisture gradient in wood. M. Tiitta et al., *Development of an Electrical Impedance Spectrometer for the Analysis of Wood Transverse Moisture Gradient*, *in* PROCEEDINGS OF THE 12TH INT'L SYMPOSIUM ON NONDESTRUCTIVE TESTING OF WOOD (Sept. 13-15, 2000). Electrodes contained in a probe are placed on the wood surface. One electrode transmits an

electrical signal at frequencies below 5 MHz, and the second receives the signal. A variable electric field is developed between the electrodes. Analysis of the behavior of impedance, or signal strength, for the various frequencies transmitted through the wood allows estimation of the moisture gradient within the wood. This device was developed to sense the moisture gradient in logs.

Writings by *Sobue* and *Jazayeri et al.* have demonstrated a method to sense the moisture gradient in wood by what *Sobue* termed Electrode Scanning Moisture Analysis (ESMA). N. Sobue, *Measurement of Moisture Gradient in Wood by Electrode Scanning Moisture Analysis ESMA*, *in* PROCEEDINGS OF THE 12[TH] INT'L SYMPOSIUM ON NONDESTRUCTIVE TESTING OF WOOD (Sept. 13-15, 2000); S. Jazayeri & K. Ahmet, *Detection of Transverse Moisture Gradients in Timber by Measurements of Capacitance Using a Multiple-Electrode Arrangement*, 50 FOREST PROD. J. 27-32 (2000). ESMA determines MC at various depths through wood thickness by manipulating the distance between adjacent electrodes on a single wood surface between 0.43 in. (11 mm) and 1.97 in (50 mm), shown in Figure 1. Examination of the capacitance changes developed by manipulation of electrode distance allows computation of wood moisture gradient at various depths through wood thickness. *Sobue*'s method allowed measurement of MC in wood up to 120 percent. *Sobue* and *Jazayeri et al.*, however, demonstrated that this method would work for only a single wood density in which MC levels were manipulated.

The *Tiitta et al.*, *Sobue*, and *Jazayeri et al.* devices are adjacent electrode impedance devices that are designed to estimate moisture gradient rather than average MC. The ability to estimate wood density as well as moisture gradient was not demonstrated by this device. By contrast, Applicant's invention is an opposed or adjacent plate capacitance device that senses mean MC and may also provide an estimate of wood

density. Neither the *Tiitta et al.*, *Sobue*, or *Jazayeri et al.* devices employ phase shift to improve their estimate of MC or to provide an estimate of wood density.

U.S. Patent 5,585,732 to *Steele et al.* and two writings by *Steele et al.* have disclosed a method for detecting density differences in scanned lumber by a radio frequency method with opposed electrodes. P. Steele & J. Cooper, *Estimating Strength Properties of Lumber with Radio Frequency Scanning*, *in* PROC. OF THE 4TH INT'L CONFERENCE ON IMAGE PROCESSING AND SCANNING OF WOOD (Aug. 21-23, 2000); P. Steele et al., *Differentiation of Knots, Distorted Grain, and Clear Wood by Radio-Frequency Scanning*, 50 FOREST PROD. J. 58-62 (2000). To date, only detection of knots and voids has been described as being detected. The application of phase shift or loss tangent to assist in more accurately estimating dielectric material MC or estimating density has not been disclosed for this or any other radio frequency device.

The disclosures by *Steele et al.* employed dielectric properties and wood density in the estimation of wood strength by radio frequency capacitance employing a variation of the *Steele et al.* device. However, the *Steele et al.* method depended on prior knowledge of wood MC with statistical correction for the known MC differences. Validation of this method showed an $R^2$ value of 0.67 between attenuated dielectric signal and lumber modulus of rupture. Only a single radio frequency signal attenuation measurement to provide specific gravity estimates was employed. Applicant's invention, by contrast, may employ single or multiple radio frequency signals to obtain dielectric constant. The *Steele et al.* method did not measure phase shift to improve the estimate of wood density.

*Wood Strength Estimation Based On Density Detection*

The amount of lumber graded by machine stress rating (MSR) has continued to increase since the development of the technology in the early 1960's. This growth has been driven by the significant premium in value for MSR versus visually graded lumber in certain lumber grades. MSR graded lumber is mechanically flexed to obtain a flatwise modulus of elasticity. In a 1968 writing, *Muller* teaches a method of estimating lumber grade based on the known relationship between modulus of elasticity and modulus of rupture combined with additional information from visual inspection of the lumber. P. Muller, *Mechanical Stress-Grading of Structural Timber in Europe, North America and Australia*, 2 WOOD SCI. & TECH. 43-72 (1968). In addition, in 1997 *Biernacki et al.* indicated a significant potential for increased lumber value from improved accuracy in lumber grading. $R^2$ values based on relating modulus of elasticity to modulus of rupture are species dependent but are approximately 0.50. J. Biernacki *et al.*, *Economic Feasibility of Improved Strength and Stiffness Prediction of MEL and MSR Lumber*, 47 FOREST PROD. J. 85-91 (1997).

U.S. Patent 4,941,357 to *Schajer* discloses an alternative to MSR lumber grading that is a system that estimates lumber strength based on x-ray through-lumber-thickness scanning. By this method the lumber strength is estimated by assigning a clear wood strength value with deductions based on knot presence indicated by specific gravity scans. Lumber strength estimations based on x-ray scanning is reported to be higher than MSR estimates with $R^2$ values ranging between 0.68 and 0.78 for southern yellow pine lumber.

Applicant's invention has potential as an MSR device capable of predicting clear wood density. In such use, Applicant's invention will require a knot detection system such as a digital camera, ultrasound, radio frequency, infrared, etc. MSR

lumber grading requires information on knot size and location in addition to density of clear wood. Also required will be techniques and software to correct for knot influence on lumber strength.

**Background of the Technology**

After logs are milled and lumber is created, the lumber is usually dried. Softwood lumber is a challenge to dry, and hardwood lumber is even more difficult. A key difference between hardwood and softwood lumber drying is the initial moisture content (MC) at the start of kiln drying. Wood MC may vary from 0% to a "green" measure. A green measure of MC may be as high or higher than 200 percent. Softwood lumber is dried green immediately after it is sawn. The average initial MC of softwood lumber is often greater than one-hundred percent, based on oven-dry weight. Typically, hardwood lumber has a significantly lower initial MC than softwood lumber. When dried directly from the saw, hardwood lumber is typically between sixty and eighty percent MC while softwood lumber frequently exceeds 100 percent MC. Often, hardwood lumber is air dried to reduce its initial MC to approximately 25 percent before being dried. In contrast, softwood lumber is often dried green at, or above, 100 percent MC.

Lumber in dry kilns can be monitored for drying rate and for final moisture content (MC) at the drying schedule endpoint by either MC schedules or time-based schedules. MC schedules monitor the rate of drying by periodically weighing previously cut short lumber samples during drying to measure the MC. Time-based schedules do not require lumber samples, but instead assume that the rate of drying

is correlated with kiln conditions and the time over which the conditions are applied to the lumber. Time-based schedules are widely used in the drying of softwood lumber because softwood lumber is less susceptible to drying degrade caused by drying the wood at an improper rate. However, failure to control the drying rate when applying pre-set time schedules is responsible for considerable lumber degrade during drying. In order for time-based schedules to work well, each lumber load placed in the kiln must have approximately the same initial MC, the same permeability, and kiln conditions must be identical from charge to charge. These requirements are not always satisfied and lumber drying degrade often occurs.

For most hardwood species, MC schedules must be used to prevent dramatic value losses from drying degrade. Traditional MC schedules require the kiln operator to control the drying rate by monitoring the MC of several kiln samples. These samples are two to three-feet long and are dried with the kiln charge of lumber. Prior to the start of drying, a MC section is cut from each kiln sample. This section is rapidly oven dried to determine the initial MC of the wood going into the kiln. This initial MC value is used in conjunction with the sample weight to determine the samples' MC throughout the drying run. This continual monitoring allows control of the kiln conditions, and the lumber's drying rate is based on the average sample MC.

The process of monitoring kiln samples requires kiln operators to repeatedly enter the dry kiln to remove kiln samples for monitoring by weighing. Following weighing, the kiln samples must be returned immediately to the dry kiln. Softwood lumber of nominal two-inch thickness is dried at high temperatures from green wood and the drying process usually requires less than 24 hours. In the case of air-dried

hardwoods of four-quarter-inch thickness, the approximate drying time is between four and eleven days.

Monitoring MC samples over a short-time interval (24 hours or less) makes it difficult for operators to apply MC schedules for softwoods without additional technology. For both hardwood and softwood, kiln drying technological developments in recent years have produced several new methods to estimate the MC drying rate and drying end point. Reports on the effectiveness of these systems has been provided by *Culpepper*. L. Culpepper, HIGH TEMPERATURE DRYING 258-262 (1990).

One method for estimating the MC drying rate is temperature drop-across-the-load monitoring, which monitors the temperature of the air flowing across the drying lumber. The air temperature decrease from lumber entry to lumber exit is closely correlated to the wood MC for MC below the fiber saturation point, but the method is inaccurate above the fiber saturation point.

Another method for estimating the MC drying rate uses electrical resistance devices and employs pairs of pins inserted into holes drilled into the lumber. The distance between the pins is limited (1" to 2") to allow an applied low voltage to flow between the two pins. The resulting resistance is measured and correlated to wood MC. The resistance devices accurately predict the MC below the fiber saturation point, but inaccurately predict the wood MC above the fiber saturation point.

An additional method uses an electrical capacitance method to measure the capacitance between plates inserted in the stack and kiln rails which are grounded. This method has been shown to provide a MC measurement that is often not accurate.

Weight-based systems are another method used to measure wood MC. These systems measure the total weight of kiln lumber during drying. This allows close monitoring of the drying rate. These systems are reportedly accurate, but problems with sensor durability in the harsh kiln environment and the relatively high cost of using weight-based systems has limited their widespread adoption.

A more recent weight-based system not reviewed by Culpepper monitors the weight of a kiln sample suspended in the kiln plenum, which is the space around the lumber. This system is reportedly effective but the relatively high cost of the system has limited its adoption.

As summarized above, systems that measure MC during kiln drying to monitor drying rate and drying end point are available. However, these systems are relatively expensive and not always effective at monitoring wood MC. There exists a need for improved methods to monitor drying rate and drying end point.

The ability to estimate wood density is also needed in the wood processing industry. The term density as employed herein refers to the oven-dry specific gravity of a dielectric material. A dielectric material is a material that does not conduct electricity. For hygroscopic materials that readily absorb water, such as wood, the specific gravity differs from the density when the material MC is greater than zero. Wood density varies significantly, both between and within species. In addition to the need to detect the MC and/or density of lumber, there exists a need to detect the MC and/or density of wood particles and flakes, wood composite products, and other dielectric materials (such as rubber, plastics, and foods).

## SUMMARY OF THE INVENTION

The present invention, a Moisture and Density Detector (MDD), can provide a method and apparatus to determine the MC and/or density of any dielectric material for various purposes. Examples of dielectric materials that can be used with the MDD include, but are not limited to, wood-based materials, wood composites, agricultural and food products, plastic, and rubber.

The present invention can sense the dielectric response of a radio frequency signal passed between opposed or adjacent capacitance electrodes and can measure the signal strength and phase shift of the signal. The addition of phase shift and multiple frequencies can improve the accuracy of the results of this type of device for multiple layer scanning.

Although the MDD can be used for any dielectric material, it is very useful in detecting the moisture content (MC) of wood and wood-based materials. In particular, the MDD can be used to detect the MC and/or density of lumber in a dry kiln prior to, during, and/or following drying. In addition, the MDD can detect the MC and/or density for the purpose of assigning lumber or veneer strength grades. The MDD can also detect MC and/or density of lumber, logs, poles, flakes, particles, composite panels, or any other form of solid wood product for any other purpose.

The MDD can also be used to monitor green wood MC prior to and following drying. In this case lumber, veneer, flakes, particles, etc. can be monitored and subsequently sorted on the basis of MC. Green sorting of lumber by weight is commonly done at sawmills that wish to maximize kiln capacity. Lumber with different MCs can be dried separately allowing lumber with lower MC to be dried

more rapidly. Dry sorting to detect wet wood both between and within individual pieces of lumber to identify those pieces requiring further drying is also a potential application.

In addition, the MDD can be used as a machine stress rating (MSR) device by which lumber strength is assessed based on density. A MSR device is commercially available that employs x-rays for this purpose, but no radio frequency device is available.

The above and other objects and advantages of the present invention will become more apparent from a reading of the following detailed description of the invention in conjunction with the drawings and appended claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure **1** displays an exemplary embodiment of an adjacent electrode radio-frequency device.

Figure **2** displays an exemplary embodiment of a parallel opposed electrode device.

Figure **3** displays a diagram of an exemplary embodiment of the present invention, a Moisture and Density Detector (MDD).

Figure **4** displays a diagram of another exemplary embodiment of the Moisture and Density Detector (MDD).

Figure **5** is a flowchart illustrating an exemplary process for determining the moisture content (MC) and/or density of any dielectric material.

Figure **6** is a flowchart illustrating an exemplary process for step **525** of Figure **5**.

Figure **7** is a flowchart illustrating an exemplary process for step **605** of Figure **6**.

Figure **8** is a flowchart illustrating an exemplary process for step **615** of Figure **6**.

## DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed to an apparatus and method for estimating moisture content (MC) and/or density of dielectric materials. The present invention can sense the dielectric response of a radio frequency signal passed through the dielectric material. A radio frequency signal can be passed between opposed or adjacent capacitance electrodes and can measure the signal strength and phase shift of the signal. The addition of phase shift and multiple frequencies can improve the accuracy of the results of this type of device for multiple layer scanning.

Although the MDD can be used for any dielectric material, it is very useful in detecting the moisture content (MC) and/or density of wood and wood-based materials. In particular, the MDD can be used to detect the MC and/or density of lumber in a dry kiln prior to, during and/or following drying.

Figure 1 displays an exemplary embodiment of an adjacent electrode radio-frequency device. The terms *adjacent electrode* and *opposed electrode* denote the relative position of electrodes with respect to each other. In an alternative preferred embodiment, the electrodes may also be comprised of one or more adjacent pairs of

electrodes or opposed and adjacent pairs of electrodes may be combined in the same device.

The electrodes **110** and **120** are used for transmitting and receiving the radio frequency signal **105** through the dielectric material. The electrodes **110** and **120** may be of any shape and size and constructed of any electrically conductive material. Other materials may be incorporated into the electrodes **110** and **120**. The electrodes **110** and **120** may be positioned at a distance from the dielectric material surface or may be in direct contact. The electrodes **110** and **120** may be comprised of brushes, rolling transducers, or be of any other type. Capacitance, and therefore signal strength, is increased as plate size and material conductivity increases.

In one exemplary embodiment, the MDD can use an electrode shape that is rectangular and 3.0-inch by 9.0-inch in dimension. A long axis of plate is aligned with a long axis of lumber. The plates can be positioned 0.250 inch from a lumber surface, but direct contact is also feasible for stationary wood scanning. The actual distance that the electrodes **110** and **120** are positioned from the surface of the dielectric material may vary depending on the signal strength, frequency applied, or need of the specific application.

In another exemplary embodiment, the MDD can use an electrode shape of steel brushes applied to a wood surface. Brushes can be applied in both the adjacent and opposed method.

In an alternate exemplary embodiment, the transmitting electrode **110** may temporarily become a receiving electrode **120** and the receiving electrode **120** can

become a transmitting electrode **110**. This alteration in roles would be achieved by software or electronic switching, and would be obvious to one experienced in the art.

In yet another exemplary embodiment, the MDD can measure the MC and/or density of each face of a dielectric material. In the case of wood, for example, compression wood, wet wood, and juvenile wood all differ in MC and density from normal wood. A piece of lumber may be composed of normal wood on one face and compression wood, wet wood or juvenile wood on another. Application of adjacent electrodes on each board face would allow comparison of differences in MC and/or density between the two faces. This would allow determination of the presence of these wood types on a single lumber face.

Figure 1 shows an adjacent electrode configuration in which both electrodes **110** and **120** are positioned on the same side of the wood surface **130**. A radio frequency signal generating device **140** generates a radio frequency signal **105** that is applied to the transmitting electrode **110** and sensed by the receiving electrode **120** through an electric field **150**. The radio frequency signal **105** penetrates the wood **130** on the side on which the electrodes **110** and **120** are positioned.

Figure **2** displays an exemplary embodiment of a parallel opposed electrode device. Electrodes **110** and **120** are positioned on opposite sides of the wood material **130**. A radio frequency signal generating device **140** generates a radio frequency signal **105** that is applied to the transmitting electrode **110** and transmitted through the wood material **130** through the electric field **150**. The radio frequency signal **105** penetrates through the wood material from one side to the other.

Figure **3** displays a diagram of an exemplary embodiment of the present invention, a Moisture and Density Detector (MDD). Figure **3** displays the architecture of the present invention. A radio frequency signal **105** moves through this apparatus. The apparatus is a MC and/or density detector comprised of: a means for generating a radio frequency signal **140**; one or more pairs of electrodes **110** and **120**; an electric field **150** passing through the wood material; a means for measuring the radio frequency signal **160**; and a means for comparing the measured radio frequency signal to predetermined values **180**.

The radio frequency signal **105** can be one or multiple radio frequency signals **105**. The frequency range claimed is the radio frequency range above the direct current (DC) and up to and including 1000 MHz. Knot presence in lumber may increase or decrease the strength of the dielectric signal depending on the knot characteristics relative to the clear wood. Likewise, a void in the lumber will decrease the strength of the radio frequency. For the purpose of kiln monitoring an operator can easily avoid placement of plates over knots or voids. For lumber sorters in which lumber is passed at speed past electrodes a method to eliminate knots from the data may be preferable. For this purpose, knot and void detection equipment such as a digital camera, ultrasound, x-ray, other radio frequency device, or any other device may be employed.

The means **160** for measuring the signal strength and phase shift of the radio frequency signal **105** measures the signal strength and phase shift caused by the interaction of the radio frequency signal **105** with the dielectric material.

The means for comparing the measured radio frequency signal to predetermined values **180** compares the signal strength and the phase shift of the radio frequency signal **105** to predetermined values to get an estimate of the MC and/or density.

Figure **4** illustrates a preferred embodiment of the MDD apparatus. The means for generating a radio frequency signal **105** is a signal generator **440**. An amplifier **435** can be added to amplify the radio frequency signal **105** generated by the signal generator **440**. The pair of electrodes **110** and **120** are shown with the electric field **150**. Another amplifier **435** can be added to amplify the radio frequency signal **105** after it passes between the one or more pairs of electrodes **110** and **120**, and before it is passed to the means for measuring the radio frequency signal **160.** The means for measuring the signal strength and phase shift of the radio frequency signal, or amplitude measuring and phase comparing device **160** can be an oscilloscope **460**. In this case the amplitude measuring and phase comparison is done by one device, although these measurements may each be performed by separate devices. While an oscilloscope converts analog-to-digital values automatically, other devices may not have this feature. In this case an analog to digital converter is required to convert the analog signals. The means **180** for comparing the measured radio frequency signal to predetermined values is a computer **480**, which stores the signal strength and phase shift information.

Figure **5** is a flowchart illustrating an exemplary process for determining the moisture content (MC) and/or density of any dielectric material. In step **505**, the radio frequency signal **105** in the range above the DC and up to and including 1000 MHz

is generated by a signal generator **440** and transmitted to the amplifier **435**. In step **510**, the radio frequency signal **105** is amplified by an amplifier **435** and then transmitted to the electrodes **110** and **120**. (In an exemplary embodiment the radio frequency signal is amplified. However, the amplifier **435** and amplification step **510** may be eliminated.) In step **515**, the radio frequency signal **105** is applied to the transmitting electrode **110**, creating an electric field **150** sensed by the receiving electrode **120**.

In step **520**, the radio frequency signal **105** is amplified by an amplifier **435** and then transmitted to the oscilloscope **460**. (In an exemplary embodiment the radio frequency signal is amplified. However, the amplifier **435** and amplification step **520** may be eliminated.)

In step **525**, the sensed radio frequency signal **150** from the receiving electrode **120** is input to the oscilloscope **460**. Although the oscilloscope **460** is used in an exemplary embodiment, the radio frequency signal **105** sensed by the receiving electrode may be analyzed for amplitude and phase shift response by any device capable of measuring amplitude and of comparing the phase shift caused by interaction of the wood with the radio frequency signal. In an alternative embodiment, a spectrum analyzer, or any other competent device may be employed. A dedicated device with the single function of comparing phase shift caused by material wood interaction with the radio frequency signal will likely be the least-cost solution to the phase shift measurement.

In step **530**, the computer **480** stores the digitally described signal strength and phase shift information and compares signal strength and phase shift to predetermined values to obtain estimates of MC and/or density.

Figure **6** is a flowchart illustrating an exemplary process for step **530** of Figure **5.** In step **605**, predetermined values needed to estimate the MC and density are developed. While in the exemplary embodiment provided below, the MDD used regression equations to estimate MC and density, such regression equations may not be required. Threshold values, physical constants, or any other values may be applied to correlate predetermined signal strength and phase shift values that will allow correlation of measured MC and density values to MC and density. Such values may be obtained by empirical observation or by theoretical analysis based on known physical relationships of the dielectric material. In step **610**, phase shift and signal strength values are measured and entered into the computer **480.** In step **615**, the measured phase shift and signal strength values are compared to the predetermined values to determine the MC and/or density estimates.

Figure **7** is a flowchart illustrating an exemplary process for step **605** of Figure 6. In step **705**, relevant criteria, including phase shift and signal strength, are measured using a known MC. For example, the MDD can measure the observed phase shift and signal strength values of each species of solid wood, the range of specific gravity values each species may exhibit, and all MC values the wood may exhibit. Plate material, size, shape, distance from wood surface, signal strength and frequencies employed are made to be identical to those to be applied by the device in practice. In step **710**, regression equation model 1 is developed using the relevant

criteria. In the example for wood, the regression equation is developed using this criteria for each species of wood and for the range of MC. In step **715**, data and the regression equation model 1 is stored on the computer **480.**

To illustrate how Figure **7** can be applied in an exemplary embodiment, we will use the example of how the database information is compiled for the southern yellow pine lumber. In step **705**, green lumber is selected from a sawmill with an attempt to sample as wide a specific gravity range as possible. Prior to drying, the green lumber is placed between the electrodes **110** and **120** to determine the influence of the MC and specific gravity of each piece on the signal strength and phase shift of the radio frequency signal **105**. The lumber specimens are dried and periodically removed from the oven and weighed and scanned by the MDD. The periodic removals are of such a length to allow approximate reduction in MC of about 2 percent between MDD scanning. Frequencies applied are 0.25, 0.50, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 MHz. Initial applied voltage is 75 volts and radio frequency amplifier output power level is 10 watts. Electrode plate material is stainless steel of rectangular 3.0 inch by 9.0 inch in dimension. Plate thickness is 0.0625-inch. The lumber is to be slowly dried in an oven at 150°F.

In step **710**, the regression equation Model 1 coefficients are estimated based on the data explained above, for the described variables of the MDD. The estimated regression equation Model 1 coefficients are employed to predict MC. In step **715**, the resulting data and regression equation Model 1 are stored on the computer **480**.

Figure 8 is a flowchart illustrating an exemplary process for step 615 of Figure **6.** In step **805**, regression equation Model 1 coefficients are used to calculate MC

estimates. In step **810**, a restricted MC range is identified about the MC estimates. In step **815**, a reduced data set corresponding to the MC values with the restricted MC range is segregated from the total data. In step **820**, a regression equation Model 2 is estimated based on the reduced data set. In step **825**, the regression equation Model 2 coefficients are used to calculate specific gravity estimates based on measured values.

The following example illustrates how Figure **8** can be applied in an exemplary embodiment. In step **805**, the entered data used regression equation Model 1 coefficients to calculate an estimated MC of 80 percent. In step **810**, a reduced set of MC data defined by a ±5 percent range about the 80 percent MC estimate is identified. In step **815**, the data corresponding to the MC values in the reduced data set is segregated from the total data set. In step **820**, The $R^2$ value for the regression equation Model 2 is estimated to be 0.99. In step **825**, the regression equation Model 2 coefficients are used to calculate a specific gravity estimate based on actual measured values.

**Model 1**

$$MC = \mu + F + D + D^2 + PS + PS^2 + \varepsilon$$

Where:

MC = estimated MC for loblolly pine lumber
$\mu$ = mean moisture content for loblolly pine lumber
F = applied frequency or frequencies (for this regression, data for eleven frequencies were analyzed)
D = dielectric constant (uses signal strength measured in volts)
PS = phase shift
$\varepsilon$ = error term

**Model 2**

$$SG_{mcr} = \mu + F + D + D^2 + PS + PS^2 + \varepsilon$$

Where:

$SG_{mcr}$ = specific gravity for loblolly pine lumber where $_{mcr}$ indicates a segregated data set corresponding to a restricted MC range identified about the MC value estimated by regression equation Model 1
$\mu$ = mean specific gravity for loblolly pine lumber
other variables are as previously defined in Model 1.

**WHAT IS CLAIMED IS:**

1. An apparatus for estimating at least one of moisture content and density of a dielectric material, comprising:

a generator for generating a radio frequency signal in the range above DC and up to and including 1000 MHz;

at least one pair of electrodes for transmitting and receiving said radio frequency signal through said dielectric material;

a meter for measuring signal strength and phase shift of said radio frequency signal caused by interaction of said dielectric material; and

a micro-processor for comparing said measured signal strength and phase shift of said radio frequency signal to predetermined values.

2. The apparatus of Claim 1, wherein the electrodes are adjacent electrodes.

3. The apparatus of Claim 1, wherein the electrodes are opposed electrodes.

4. The apparatus of Claim 1, further comprising:

at least one amplifier for amplifying said radio frequency signal.

5. The apparatus of Claim 4, wherein the at least one amplifier is added after the generator, and before the at least one pair of electrodes.

6. The apparatus of Claim 4, wherein the at least one amplifier is added after the at least one pair of electrodes, and before the meter.

7. The apparatus of Claim 1, wherein the meter is an oscilloscope.

8. A method for estimating at least one of moisture content and density of a dielectric material, comprising;

generating a radio frequency signal in the range above DC and up to and including 1000 MHz;

applying said radio frequency signal to at least one pair of electrodes for transmitting and receiving said radio frequency signal through said dielectric material;

measuring signal strength and phase shift of said radio frequency signal caused by interaction of said dielectric material; and

comparing said measured signal strength and phase shift of said radio frequency signal to predetermined values to determine at least one of moisture content and density values.

9. The method of Claim 8, further comprising:

amplifying said radio frequency signal.

10. The method of Claim 9, wherein said radio frequency signal is amplified after generating said radio frequency signal, and before applying said radio frequency signal to the at least one pair of electrodes.

11. The method of Claim 9, wherein said radio frequency signal is amplified after the at least one pair of electrodes, and before the meter.

12. The method of Claim 8, wherein the step of comparing said measured signal strength and phase shift of said radio frequency signal to predetermined values to determine at least one of moisture content and density values further comprises:

developing predetermined values of said signal strength and phase shift for said dielectric material;

measuring the signal strength and phase shift of a radio frequency signal caused by interaction of said radio frequency signal with said dielectric material; and

comparing said measured signal strength and phase shift with said predetermined values to determine at least one of moisture content and density range for said dielectric material.

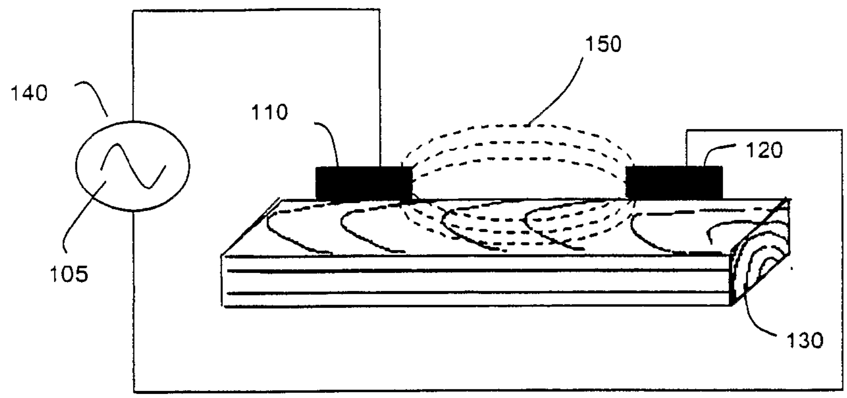
13. The method of Claim 12, wherein the step of developing predetermined values of said signal strength and phase shift for said dielectric material comprises:

measuring said signal strength and phase shift for said dielectric material using a known moisture content;

using a regression equation to determine an unknown moisture content for said dielectric material; and

using a regression equation to determine density for said dielectric material.

# FIGURE 1




# FIGURE 2

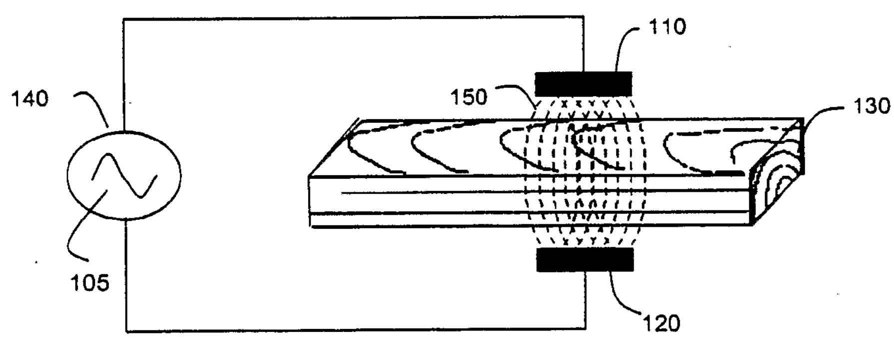
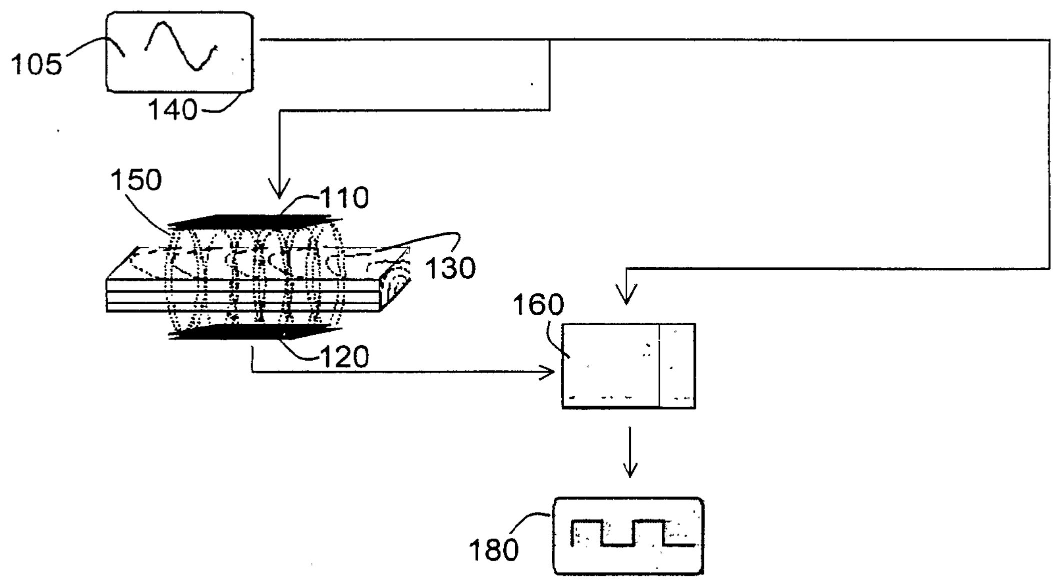


FIGURE 3



# FIGURE 4

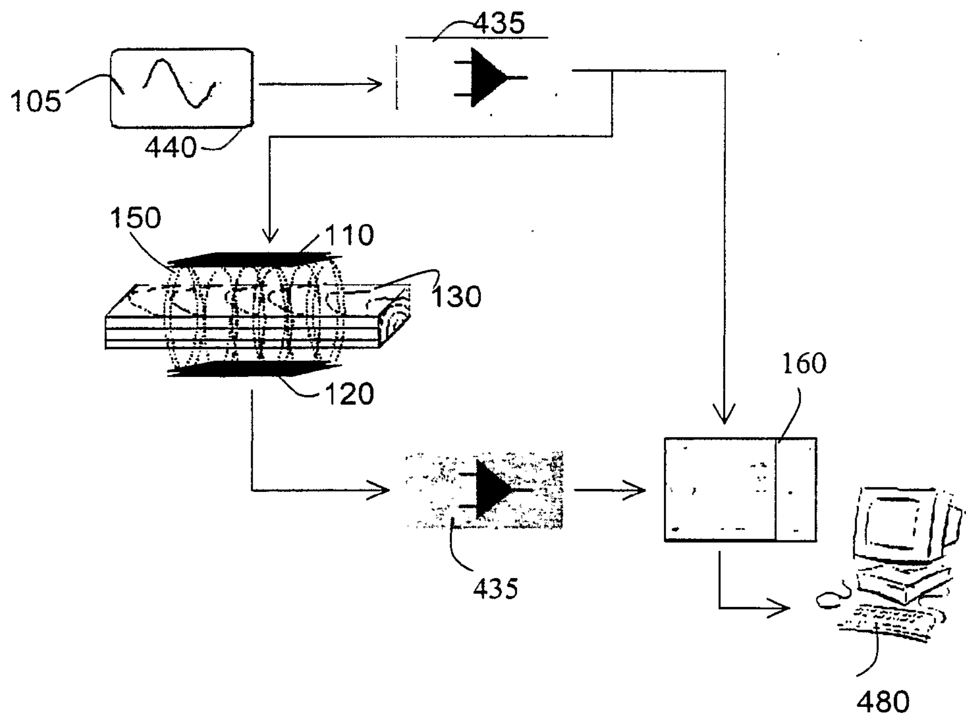


FIGURE 5

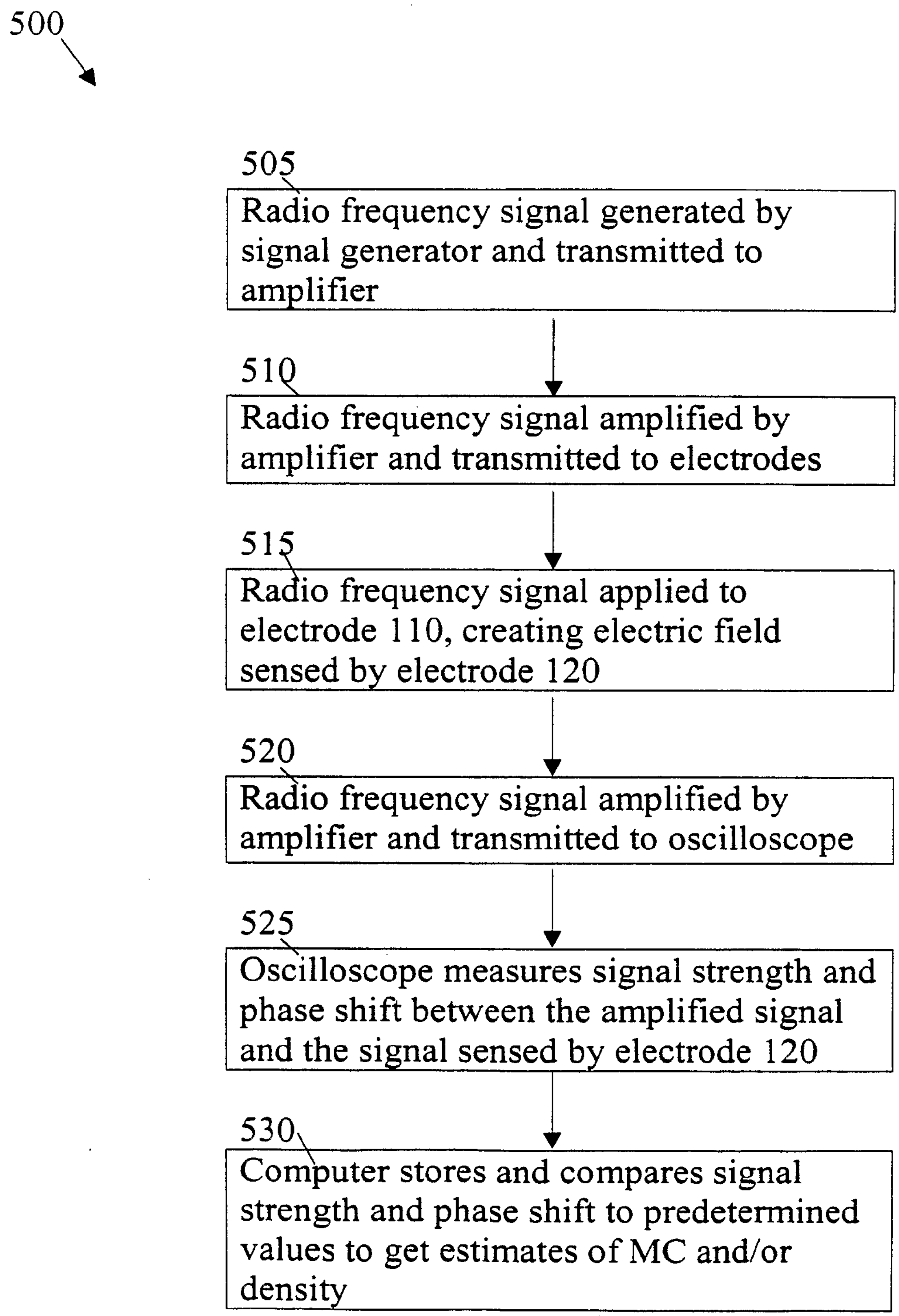
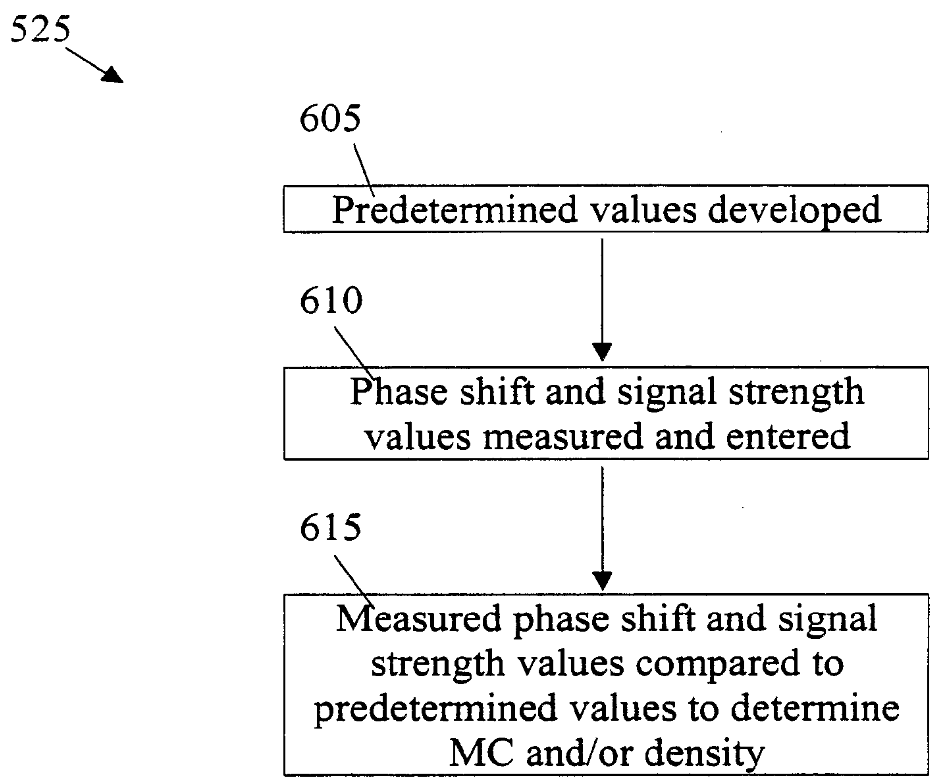

500
505
Radio frequency signal generated by signal generator and transmitted to amplifier
510
Radio frequency signal amplified by amplifier and transmitted to electrodes
515
Radio frequency signal applied to electrode 110, creating electric field sensed by electrode 120
520
Radio frequency signal amplified by amplifier and transmitted to oscilloscope
525
Oscilloscope measures signal strength and phase shift between the amplified signal and the signal sensed by electrode 120
530
Computer stores and compares signal strength and phase shift to predetermined values to get estimates of MC and/or density

FIGURE 6


525
605
Predetermined values developed
610
Phase shift and signal strength values measured and entered
615
Measured phase shift and signal strength values compared to predetermined values to determine MC and/or density

# FIGURE 7

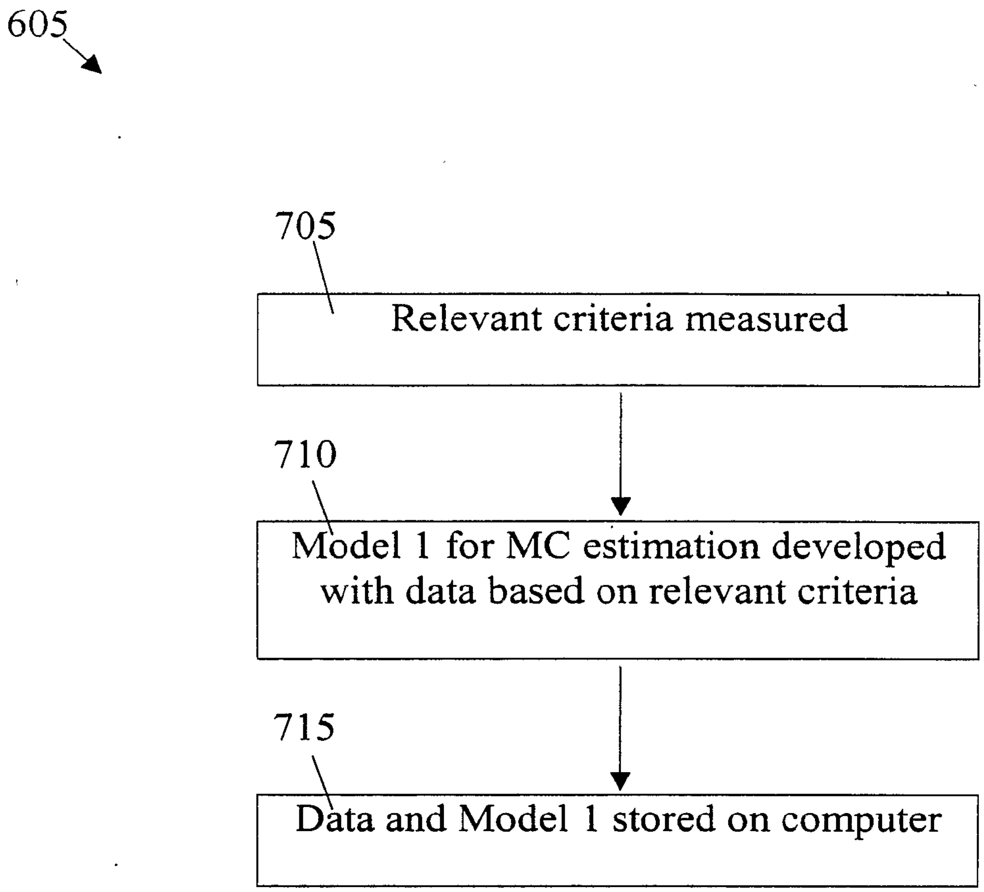
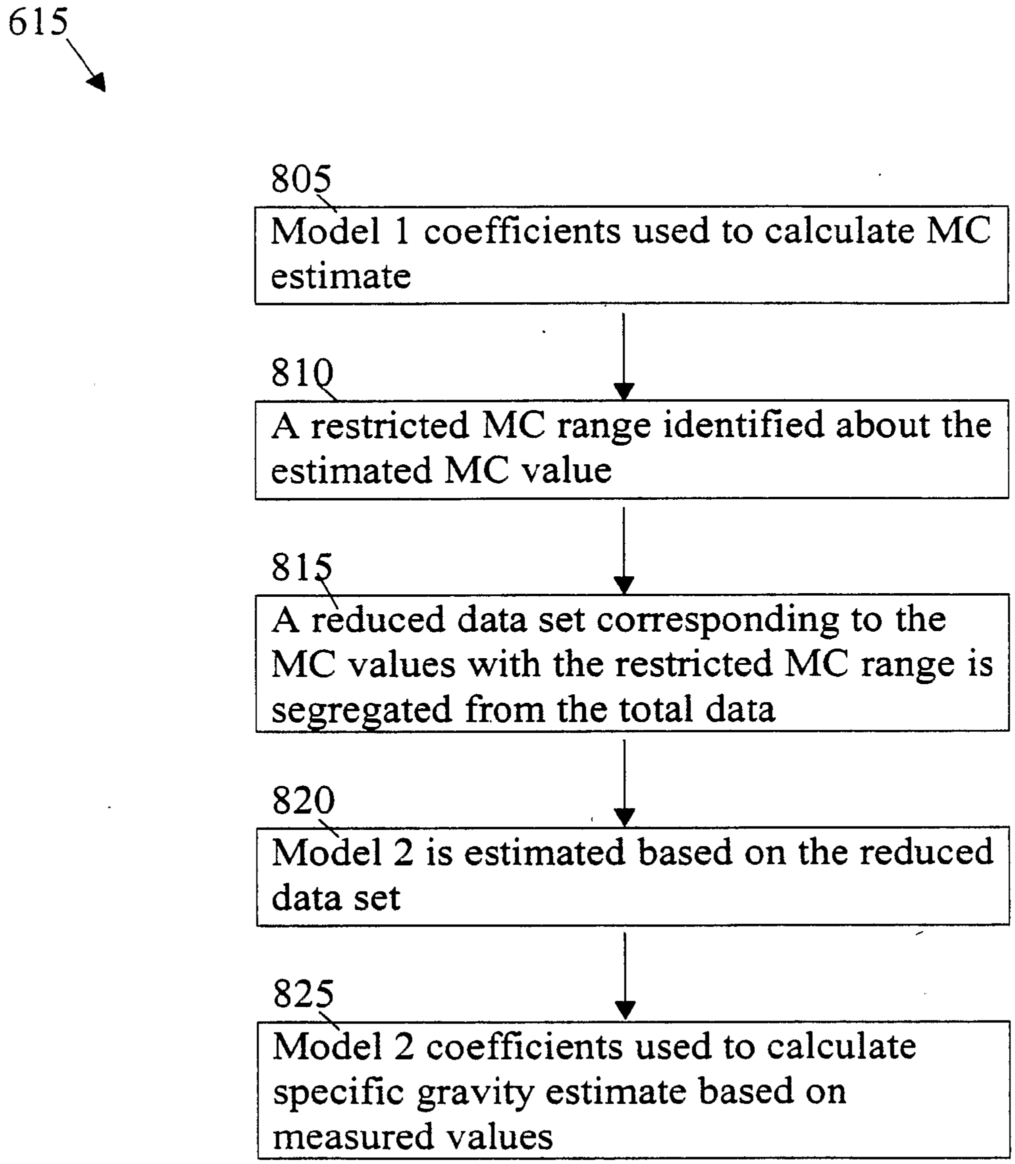

605
705
Relevant criteria measured
710
Model 1 for MC estimation developed with data based on relevant criteria
715
Data and Model 1 stored on computer

FIGURE 8


615
805
Model 1 coefficients used to calculate MC estimate
810
A restricted MC range identified about the estimated MC value
815
A reduced data set corresponding to the MC values with the restricted MC range is segregated from the total data
820
Model 2 is estimated based on the reduced data set
825
Model 2 coefficients used to calculate specific gravity estimate based on measured values